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Jhoon Kim

Andrew F. Nagy

Jane L. Fox

Wright State University - Main Campus, jane.fox@wright.edu

Thomas E. Cravens

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Solar cycle variability of hot oxygen atoms at Mars

Jhoon Kim,¹ Andrew F. Nagy,² Jane L. Fox,³ and Thomas E. Cravens⁴

Abstract. The population of hot oxygen atoms in the Martian exosphere is reexamined using newly calculated hot O production rates for both low and high solar cycle conditions. The hot oxygen production rates are assumed to result from the dissociative recombination of O_2^+ ions. These calculations take into account the calculated vibrational distribution of O_2^+ and the new measured branching ratios. Furthermore, these calculations also consider the variation of the dissociative recombination cross section with the relative speed of the participating ions and electrons, the rotational energy of the O_2^+ ions, and the spread of the ion and electron velocities. These production rates were next used in a two-stream model to obtain the energy dependent flux of the hot oxygen atoms as a function of altitude. Finally, the calculated flux at the exobase was input into an exosphere model, based on Liouville's theorem, to calculate the hot oxygen densities as a function of altitude in the exosphere and the resulting escape flux. It was found that hot oxygen densities vary significantly over the solar cycle; the calculated densities vary from about 2×10^3 to 6×10^3 cm^{-3} at an altitude of 1000 km. The escape flux also varies from about 3×10^6 to 9×10^6 $\text{cm}^{-2} \text{s}^{-1}$.

1. Introduction

The distribution of nonthermal atmospheric constituents and their escape are important for a number of different reasons, such as atmospheric evolution and the interaction of the non-magnetic planets with the solar wind. For Venus it has been well established by both observations [Nagy *et al.*, 1981] and theoretical calculations [Nagy *et al.*, 1981; McElroy *et al.*, 1982; Nagy and Cravens, 1988; Nagy *et al.*, 1990] that hot oxygen is an important constituent in the exosphere. McElroy [1972] suggested that a hot oxygen population is likely to be present around Mars. Since this early suggestion a number of other theoretical model calculations [Nagy and Cravens, 1988; Nagy *et al.*, 1990; Ip, 1990; Lammer and Bauer, 1991] of hot oxygen and hydrogen populations have been published, showing that while hot oxygen is expected to be an important constituent in the Martian exosphere, hot oxygen is not the major constituent over any altitude region. However, no observation of the hot oxygen population is available to date. The presence of an extended neutral corona plays an important role in mass loading and slowing down the solar wind at Venus and Mars. Recent MHD model calculations have shown that mass loading of the solar wind by hot oxygen is important and is necessary to explain the observed bow shock locations at Venus and Mars [Bauske *et al.*, 1998a,b].

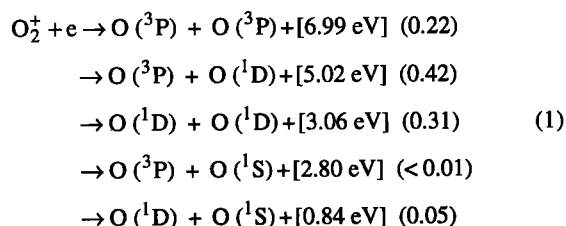
The Mars Global Surveyor (MGS), Nozomi, and Mars

Express missions are creating new interest in the upper atmosphere and exosphere of Mars. This paper describes the results of new calculations of the hot oxygen density at Mars for low and high solar activity conditions.

2. Model Description

Potential sources of hot oxygen at Mars are the dissociative recombination of O_2^+ and the charge exchange reactions of O^+ ions with H and O. However, it has been demonstrated that for Venus, Earth, and Mars, the dominant source is dissociative recombination [Nagy and Cravens, 1988; Nagy *et al.*, 1990; J. Kim, 1991; Gerard *et al.*, 1995; Richards *et al.*, 1994; Hickey *et al.*, 1995], and therefore in this work it is the only source to be considered. Richards *et al.* [1994] and Hickey *et al.* [1995] have drawn attention to other sources of the hot O corona for the terrestrial case. Most important among them are quenching and other reactions of metastable species, including $O(^1D)$, $N(^2D)$ and $O(^2D)$. We have not included these sources here but will include them and dissociative recombination of NO^+ in a more complete calculation to be reported in the future.

We have computed the nascent velocity distribution of the O atoms produced in dissociative recombination, by combining a model of the vibrational distribution of O_2^+ with the branching ratios for the different potential channels indicated in (1), as measured by Kella *et al.* [1997]:



where the square brackets denote the excess energies and the round brackets show the branching ratios. We have carried out Monte Carlo calculations in which the rotational energy of the

¹Space Division, Korean Aerospace Research Institute, Taejeon, Korea.

²Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor.

³Institute for Terrestrial and Planetary Atmospheres, State University of New York at Stony Brook, Stony Brook.

⁴Department of Physics and Astronomy, University of Kansas, Lawrence.

ion and the initial velocities of the ion and electron are chosen from among a distribution characteristic of the ion and electron temperatures. Calculations were carried out for conditions appropriate to the altitude range in question every 10 km from 130 to 290 km, and the results were interpolated linearly. Further details may be found in the work of *Fox and Hac* [1997]. This calculation is similar to that carried out by *Gerard et al.* [1995], who studied the effect of the additional sources of hot O proposed by *Richards et al.* [1994] and *Hickey et al.* [1995] on the terrestrial hot oxygen corona.

The atmospheric and ionospheric parameters used in the calculations are shown in Figures 1a and 1b. The low solar activity model is based on the neutral density and temperature profiles constructed by *Fox and Dalgarno* [1979] to fit the Viking 1 measurements [*Nier and McElroy*, 1977]. The ion temperature profile is a smoothed version of that measured by the RPA on Viking 1 [*Hanson et al.*, 1977], and the adopted electron temperature values come from the observations of *Hanson and Mantas* [1988] and the model calculations of *Rohrbaugh et al.* [1979]. Further details may be found in the work of *Fox* [1993]. The high solar activity neutral temperature and density profiles are from the Mars Thermospheric General Circulation Model (MTGCM) of *Bougher and coworkers* [*Bougher et al.*, 1990; *Bougher and Shinagawa*, 1998]. The ion and electron temperatures at high solar activity were constructed to be only slightly larger than those at low solar activity but greater than the neutral temperature profile at all altitudes.

An "eroded" ionosphere is the only one assumed for the low solar activity case. By eroded ionospheres, we mean those for which a loss process for ions is assumed at high altitudes, presumably due to the interaction of the ionosphere with the solar wind. Such an interaction is characteristic of bodies without an intrinsic magnetic field [e.g., *Cloutier and Daniell*, 1979; *Luhmann*, 1990]. The eroded ionosphere is modeled by imposing maximum upward velocity boundary conditions on 11 ions for which convergence of the model could be obtained. The model ionosphere so obtained is one for which the loss rates are limited by the production rates of the ions, rather than any specific loss process. Further details may be found in the work

of *Fox* [1997]. The Viking ion density profiles (at low solar activity) have been found to be reproducible only if such a loss process is imposed [e.g., *Chen et al.*, 1978; *Shinagawa and Cravens*, 1989; *Fox*, 1993]. At high solar activity, there is no in situ data, and the plasma pressure may be large enough to withstand the solar wind. Therefore we have constructed both eroded and noneroded high solar activity models. The low and high solar activity ionospheres were obtained using the SC#21REFW and F79050N solar fluxes from Hinteregger (private communication, 1998 [see also *Torr et al.*, 1979]). The photoabsorption and electron impact cross sections for CO₂, O, Ar, N₂, CO, O₂, and NO used are those compiled by *Fox* [1982; 1993]; the H and He cross sections are from a compilation of *Kim* [1991].

The two-stream approach [*Nagy and Banks*, 1970] was used to calculate the hot oxygen fluxes, as a function of altitude and energy. The cross section for elastic collision between hot and cold oxygen atoms was taken to be 1.2×10^{-15} cm², as suggested by *McElroy et al.* [1982]. The altitude increments used in these calculations varied smoothly from 0.2 km at the lower boundary of 130 km up to 5 km at 345 km, the upper boundary. The energy grid used was 0.03 eV and covered the range from 0 to 6 eV. The exobase was taken to be at 190 and 210 km for low and high solar activity cases, respectively. In determining the exobase location we compared estimates of the mean free path and scale height, yielding the "classical" value, as well as evaluating the altitude beyond which the upflowing flux no longer had a significant effect on the exospheric densities; both methods led to roughly similar estimates. The calculated, hemispheric hot oxygen fluxes at the exobase were transformed to an energy distribution, $f(E, z)$:

$$f(E, z) = \{\Phi^+(E, z) + \Phi^-(E, z)\} / v(E) \quad (2)$$

where Φ^+ and Φ^- are the upward and downward, hemispheric fluxes, respectively, and v is the oxygen velocity corresponding to energy E . This distribution function is then fed into an exosphere model, based on Liouville's theorem, which calculates the exospheric densities.

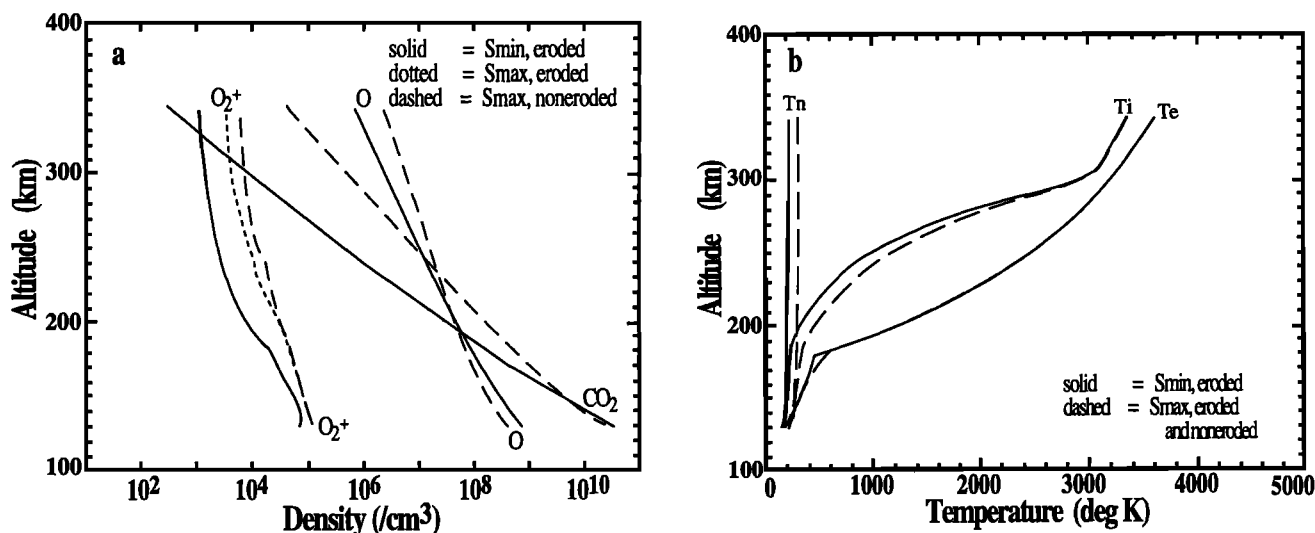


Figure 1. (a) Adopted atmospheric and ionospheric density values for high and low solar cycle conditions. (b) Adopted temperature values for high and low solar cycle conditions.

3. Results and Discussion

The calculated energy distribution functions at the exobase are shown for the three cases considered: low solar activity eroded and both eroded and noneroded high solar activity cases in Figure 2. For the sake of comparison a cold oxygen distribution corresponding to a temperature of 195 °K and a density of $2 \times 10^6 \text{ cm}^{-3}$ and a pseudo hot component for an assumed temperature of 7000 °K and a density of 10^4 cm^{-3} are also shown. The visible peaks in the distribution function near 2.5 and 3.5 eV correspond to the two branches of the dissociative recombination source with the highest branching ratios.

The calculated hot oxygen densities are plotted as a function of altitude, for the three different cases, in Figure 3. The hot oxygen densities corresponding to the low solar activity conditions are of the same general magnitude than the values calculated by us earlier [Nagy and Cravens, 1988; Nagy and Kim, 1990; Zhang *et al.*, 1993] and by Lammer and Bauer [1991]. There is a clear and significant increase in the calculated densities for the high as compared to the low solar activity case. The hot oxygen density estimates by Kotova *et al.* [1997], from the observed solar wind deceleration measurements by Phobos 2, are nearly an order of magnitude larger than even our high solar cycle values. The calculated hot oxygen densities are smaller than the estimated thermal hydrogen densities for both low and high solar activity cases. Nevertheless, it has been shown that the hot oxygen corona plays the dominant role in massloading the solar wind at Mars [Bauske, 1998b] even though thermal hydrogen is the major neutral constituent in the exosphere. For example, it was shown that in order to obtain bow shock positions consistent with the latest MGS observations [Acuna *et al.*, 1998] it was necessary to include the hot oxygen mass loading process. A comparison of the calculated hot oxygen densities with earlier density estimates for Venus indicates that at the higher altitudes the densities at Mars exceed quite significantly those at Venus. This clearly demonstrates that the hot oxygen corona is more extensive at Mars, mostly due to its smaller gravity.

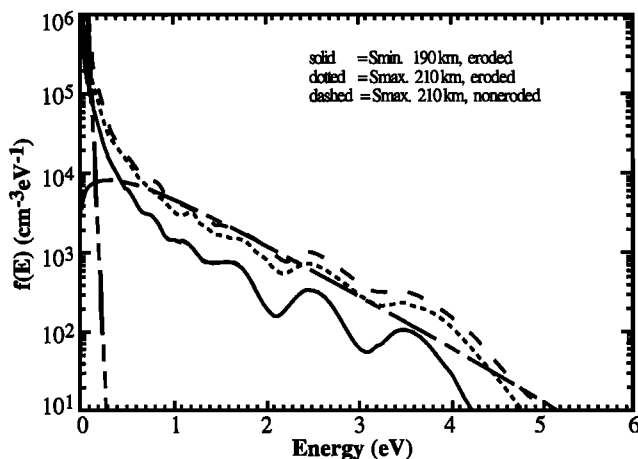


Figure 2. Calculated energy distribution of atomic oxygen at the exobase for high and low solar cycle conditions as indicated in the figure legend. The smooth long dash-short dash lines indicate a double Maxwellian fit to the calculated mean distribution, for the sake of comparison, as described in the text.

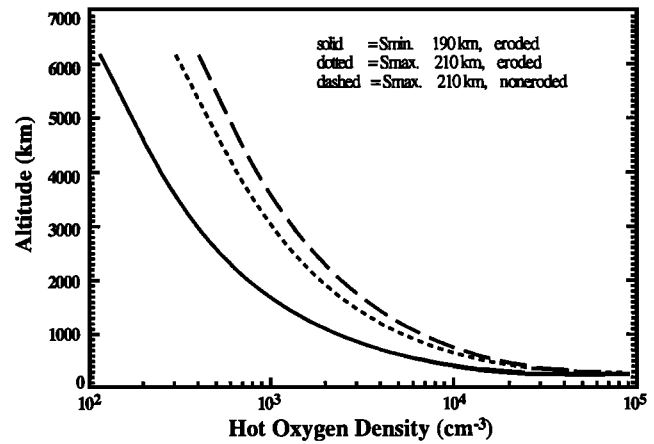


Figure 3. Calculated hot oxygen density profiles for high and low solar cycle conditions.

Integrating the upward flux of hot oxygen, with energies in excess of the escape energy, we evaluated the escape flux per unit area at the exobase; the results are shown in Table 1. It can be seen that the escape rate for the high solar activity case is greater than that for the low activity one by over a factor of 2. If one assumes that the escape flux is uniform over the entire exobase surface the total escape rate from the planet is approximately 5.3×10^{24} and 1.3×10^{25} atoms s^{-1} for the low and high solar activity cases, respectively. Although the escape flux is certainly not homogeneous over the planet, this assumption does give a useful overall estimate. This escape rate can be compared with the estimated value for oxygen ion escape, based on the measurements obtained by either the ASPERA [Lundin *et al.*, 1989] or PWS [Nairn *et al.*, 1991] instruments carried aboard the Phobos spacecraft, which was estimated to be of the order of 10^{25} atoms s^{-1} . Thus the current hot oxygen and oxygen ion escape rates appear to be of roughly the same order. Zhang *et al.* [1993] and Luhmann [1997], estimated and discussed how these escape processes may have varied over the last 3 Gyr. It was estimated that these escape mechanisms may account for the escape of up to 30 m of water over this time period; however, some estimates of the early, planetwide water inventory have been put as high as 500 to 1000 m [Carr, 1986].

The upcoming Nozomi and Mars Express missions to Mars

Table 1. Calculated Escape Flux Values

	Low Solar Activity ($Z_c=190 \text{ km}$)	High Solar Activity ($Z_c=210 \text{ km}$)	
		Eroded Ionosphere	Noneroded Ionosphere
Escape flux per unit area, atoms $\text{cm}^{-2} \text{s}^{-1}$	3.3×10^6	8.1×10^6	9.4×10^6
Total escape flux, atoms s^{-1}	5.3×10^{24}	1.3×10^{25}	1.5×10^{25}

are expected to be able to address the issue of the hot atom corona and its influence on solar wind interaction processes. As quantitative information on hot oxygen densities becomes available, it will become necessary to construct more sophisticated, three-dimensional models of the corona around Mars, in order to understand better the various processes, causing spatial and temporal variabilities. Until such a time the simple model used in the calculations presented in this paper is sufficient to demonstrate the importance of the hot oxygen population.

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T. E. Cravens, Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045.

J. L. Fox, Institute for Terrestrial and Planetary Atmospheres, State University of New York at Stony Brook, Stony Brook, NY 11794.

J. Kim, Space Division, Korean Aerospace Research Institute, 52 Euon-dong, Yusong-gu, Taejeon, Korea.

A. F. Nagy, Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI 48109. (anagy@umich.edu)

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